# A METHOD AND APPARATUS FOR DETECTING AND LOCATING NOISE SOURCES NOT CORRELATED

## FIELD OF THE INVENTION

The present invention relates to detecting and locating sources of noise in the general sense, using sensors that are appropriate for the nature of the noise source.

The invention relates to a method of detecting and locating noise sources disposed in a space of one, two, or three dimensions and optionally correlated with one another, and presenting emission spectra of narrow or broad band.

The invention finds particularly advantageous applications in the field of locating sources of noise optionally accompanied by echo and coming, for example, from vehicles, ships, aircraft, or firearms.

## BACKGROUND OF THE INVENTION

In numerous applications, a need arises to be able to locate in relatively accurate manner a source of noise in order to take measures to neutralize it. Numerous solutions are known in the prior art for acoustically locating noise sources. The main known solutions make use of techniques for correlating signals delivered by detection sensors.

Those techniques present the drawback of being particularly sensitive to interfering noise occurring in the environment of the measurement sensors. Furthermore, it must be considered that those techniques constitute specific methods that are adapted to each application under consideration.

The technique in most widespread use involves antennas having a large number of sensors (several hundred) and a large computer system implementing beam forming so as to aim in a given direction in order to increase the signal-to-noise ratio. That method does not make any *a priori* assumption concerning the number of

sources and any possible correlation between them, which leads to a loss of resolution.

## OBJECTS AND SUMMARY OF THE INVENTION

There therefore exists a need to have a general method of detecting and locating noise sources in space, when the number of noise sources is small and is known or overestimated.

The invention seeks to satisfy this need by proposing a method of detecting and locating noise sources by means of sensors adapted to the nature of the noise source, the method presenting low implementation costs.

To achieve this object, the method of the invention consists:

- in taking the time-varying electrical signals delivered by the sensors $(Y_i)$, each signal $s_i(t)$ delivered by a sensor being the sum of the signals $S_j$ emitted by the noise sources $(X_j)$;
- in amplifying and filtering the time-varying electrical signals as taken;
- in digitizing the electrical signals;
- in calculating the functional

$$f(\boldsymbol{n}_1, \ldots, \boldsymbol{n}_j, \ldots, \boldsymbol{n}_N) = \sum_{k \neq l} R_{kl}$$

with the coefficients $R_{kl}$ being a function of the vectors $\boldsymbol{n}_j$ giving the directions of the noise sources; and

- in minimizing the functional in such a manner as to determine the directions of the noise sources.

## BRIEF DESCRIPTION OF THE DRAWINGS

Various other characteristics appear from the description given below with reference to the accompanying drawing which shows embodiments and implementations of the invention as non-limiting examples.

Figure 1 is a diagram showing the principle of the detection method of the invention.

Figure 2 is a diagram showing a detail characteristic to the method of the invention.

Figure 3 is a diagram showing the method of locating two noise sources using two sensors.

MORE DETAILED DESCRIPTION

As can be seen in Figure 1, the method of the invention consists in locating noise sources $X_1$, $X_2$, ..., $X_j$, ..., $X_M$ where $j$ varies over the range 1 to $M$, the sources being distributed in space and each emitting a respective signal $S_j$ with $j$ varying in the range 1 to $M$. The method of the invention consists in locating the noise sources $X_j$ using sound wave or vibration sensors $Y_1$, $Y_2$, ..., $Y_i$, ..., $Y_N$ where $i$ varies over the range 1 to $N$, each delivering a respective time-varying electrical signal $s_1$, $s_2$, ..., $s_i$, ..., $s_N$.

The method consists in taking the time-varying electrical signals $s_i(t)$ delivered by each of the sensors and representative of the sums of the signals $S_j$ emitted by the noise sources $X_j$. The signals $s_i(t)$ received on the $N$ sensors on the basis of the sum of the contributions of the various sources is written as follows:

$$s_i(t) = \sum_{j=1}^{M} A_{ij} S_j\left(t - \frac{r_{ij}}{c}\right)$$

where $i = 1$ to $N$, $r_{ij}$ is the distance between the noise source $X_j$ and the sensor $Y_i$, and $c$ is the speed of sound in the ambient medium.

The term $A_{ij}$ represents the attenuation due to propagation together with the sensitivity factor of the sensors and is expressed as follows:

$$A_{ij} = B_i C(r_{ij})$$

where $i = 1$ to $N$ and $j = 1$ to $M$, where $B_i$ is the sensitivity coefficient of sensor $Y_i$ and where $C(r_{ij})$ is the attenuation coefficient due to propagation over a distance $r_{ij}$.

The sensors $Y_i$ are associated with respective electronic units (not shown) for amplifying and lowpass filtering the signals they pick up. The sensors are preferably matched in modulus and phase so that their sensitivities are identical. Thus, $B_i = G$ for $i = 1$ to $N$.

Advantageously, in order to facilitate implementing the antenna of sensors as defined above, the sensors $Y_i$ are placed relatively close to one another. Consequently, for remote sources, the distance $r_{ij}$ is of the order of the distance $r_j$, i.e. the distance between the center of gravity of the sensors and the source $X_j$. Thus, attenuation becomes a function of the distance $r_j$ only with $C(r_{ij}) = C(r_j)$, with $i = 1$ to $N$ and $j = 1$ to $M$.

It can be deduced therefrom that:

$$A_{ij} = G.C(r_j) = a(r_j)$$

where $i = 1$ to $N$ and $j = 1$ to $M$ and:

$$s_i(t) = \sum_{j=1}^{M} a(r_j) S_j\left(t - \frac{r_{ij}}{c}\right)$$

where $i = 1$ to $N$.

Since the amplitudes of the sources $X_j$ are unknown, the following equation can be written as follows, integrating the term $a(r_j)$ in $S_j$:

$$s_i(t) = \sum_{j=1}^{M} S_j\left(t - \frac{r_{ij}}{c}\right)$$

where $i = 1$ to $N$.

Using Fourier transforms, the expression for the signals $s_i(t)$ becomes:

$$(1) \qquad \hat{s}_i(\omega) = \sum_{j=1}^{M} \hat{S}_j(\omega) . e^{-J\omega\frac{r_{ij}}{c}}$$

where $i = 1$ to $N$

where $\hat{s}$ and $\hat{S}$ are the Fourier transforms of $s$ and $S$ respectively and where $\omega$ is angular frequency.

This first equation (1) relates the received signals to the distance $r_{ij}$, i.e. to the positions of the sources $X_j$.

As can be seen in Figure 2, other relationships can be expressed, associated with geometrical considerations enabling the distances $r_{ij}$ to be related to the unit vector $\boldsymbol{n}_j$, which determines the direction defined by the center of gravity of the sensors and the source generating the signal $S_j$. The position of the sensors is defined by the vector $\boldsymbol{C}_i$ constructed from the positions of the sensors $Y_i$ and the position of their center of gravity. A development restricted to the first order of $r_{ij}$ then provides:

$$(2) \quad r_{ij} \approx r_j - \langle \boldsymbol{n}_j, \boldsymbol{c}_i \rangle$$

where $i$ = 1 to $N$ and $j$ = 1 to $M$, and where <., .> is the scalar product.

Thus, by replacing $r_{ij}$ by the approximate expression given in (2) and integrating the phase term:

$$e^{-J\omega\frac{r_j}{c}}$$

which depends only on the source $X_j$ in the magnitude $\hat{S}_j(\omega)$, equation (1) can be written:

$$(3) \quad \hat{s}_i(\omega) = \sum_{j=1}^{M} \hat{S}_j(\omega)\, .e^{-J\omega\frac{\langle \boldsymbol{n}_j, \boldsymbol{c}_i \rangle}{c}}$$

where $i$ = 1 to $N$.

This relationship can also be expressed in matrix and vector form:

$$(4) \quad \hat{s}_i(\omega) = \sum_{j=1}^{M} \hat{S}_j(\omega)\, .\boldsymbol{T}_j(\omega)$$

with, for ith coordinate of the vector $\boldsymbol{T}_j$:

$$(\boldsymbol{T}_j)_i = e^{-J\omega\frac{\langle \boldsymbol{n}_j, \boldsymbol{c}_i \rangle}{c}}$$

where $i$ = 1 to $N$.

Or indeed:

$$(5) \quad \boldsymbol{s}(\omega) = T.\boldsymbol{S}(\omega)$$

where $T$ = matrix having the general term:

$$T_{ij} = e^{-J\omega\frac{\langle \boldsymbol{n}_j, \boldsymbol{c}_i \rangle}{c}}$$

When the sources $X_j$ are not correlated, the signals $S_j$ can be determined from the signals $s_i$ of the vectors $\boldsymbol{n}_j$. Cross-correlation functions between $S_i$ and $S_j$ for $i \neq j$ are then minimized.

Once the minimization operation has been performed, after determining the directions $\boldsymbol{n}_j$, it is also possible to discover the magnitudes $S_j$.

If $N = M$, i.e. if there are as many sensors as sources, then the system (5) can in general be inverted.

If $N \geq M$, the problem can be reduced to a square system by premultiplying by:

$$^{t}T^{*}$$

i.e. by the conjugate transposed matrix of $T$. System (5) then becomes:

$$^{t}T^{*}.\boldsymbol{s}(\omega) = {}^{t}T^{*}.T.\boldsymbol{S}(\omega)$$

I.e.

$$(6) \qquad \boldsymbol{S}(\omega) = ({}^{t}T^{*}.\mathrm{T})^{-1}.{}^{t}T^{*}.\boldsymbol{s}(\omega)$$

With the signals $\hat{S}$ expressed formally in this way, the correlation coefficients $R_{ij}$ between the sources $i$ and $j$ are calculated formally by:

$$(7) \qquad R_{ij} = \frac{\int_{-\infty}^{+\infty} \Gamma_{ij}^{2}(\tau)d\tau}{\Gamma_{ii}(0)\,.\Gamma_{jj}(0)}, \quad i \neq j$$

where $\Gamma_{ij}$ can also be calculated formally from frequency magnitudes, giving:

$$(8) \qquad R_{ij} = \frac{\int_{-\infty}^{+\infty} \left|\hat{S}_i(\omega)\right|^2.\left|\hat{S}_i(\omega)\right|^2 d\omega}{\int_{-\infty}^{+\infty} \left|\hat{S}_i(\omega)\right|^2 d\omega.\int_{-\infty}^{+\infty} \left|\hat{S}_j(\omega)\right|^2 d\omega}$$

The function for minimizing is then:

$$(9) \qquad f(\boldsymbol{n}_1, \ldots, \boldsymbol{n}_j, \ldots, \boldsymbol{n}_N) = \sum_{k \neq l} R_{kl}$$

where the coefficients $R_{kl}$ are functions of the vectors $\boldsymbol{n}_j$.

When the signals $S_i$, $S_j$ are received with comparable amplitudes, the denominators of $R_{ij}$ are of the same order of magnitude and can then be replaced by 1 without spoiling the positions of the minimas. Calculating the

$\Gamma_{ij}$ can then advantageously be performed in the time domain, when the range of variation in possible delays is small.

Once the directions defined by the vectors $\boldsymbol{n}_j$ have been determined, it is also possible to find the magnitudes $S_j$ from equation (6). Such a technique thus makes it possible to determine the natures of the sources $X_j$.

The description below with reference to Figure 3 gives an example of detecting and locating two noise sources $X_1$, $X_2$ that are not correlated ($M = 2$), using two sensors $Y_1$, $Y_2$ ($N = 2$).

In the frequency domain, the electrical signals $s_1$, $s_2$ delivered respectively by the sensors $Y_1$ and $Y_2$ and representative of the sum of the signals $S_1$, $S_2$ emitted by the noise sources $X_1$, $X_2$ are expressed as follows:

$$\begin{cases} \hat{s}_1(\omega) = e^{-J\omega\tau_{11}}\hat{S}_1(\omega) + e^{-J\omega\tau_{21}}\hat{S}_2(\omega) \\ \hat{s}_2(\omega) = e^{-J\omega\tau_{12}}\hat{S}_1(\omega) + e^{-J\omega\tau_{22}}\hat{S}_2(\omega) \end{cases}$$

where

$$\tau_{ij} = \frac{r_{ij}}{c}$$

is the propagation delay of the signal emitted by source $i$ prior to reaching sensor $j$.

Inverting this system leads to:

$$\begin{cases} \hat{S}_1(\omega) = \dfrac{\hat{s}_1(\omega)\, e^{-J\omega\tau_{22}} - \hat{s}_2(\omega)\, e^{-J\omega\tau_{21}}}{e^{-J\omega(\tau_{11} + \tau_{22})} - e^{-J\omega(\tau_{12} + \tau_{21})}} \\ \hat{S}_2(\omega) = \dfrac{\hat{s}_2(\omega)\, e^{-J\omega\tau_{11}} - \hat{s}_1(\omega)\, e^{-J\omega\tau_{12}}}{e^{-J\omega(\tau_{11} + \tau_{22})} - e^{-J\omega(\tau_{12} + \tau_{21})}} \end{cases}$$

The cross-correlation function between the source signals $S_1$ and $S_2$ is written:

$$\Gamma_{12}(\tau) = \int_{-\infty}^{+\infty} \hat{S}_1(\omega) \,.\hat{S}_2(\omega)\, e^{J\omega\tau}\, d\omega$$

for the delay $\tau$.

Replacing $\hat{S}_1(\omega)$ and $\hat{S}_2(\omega)$, it becomes:

$$\Gamma_{12}(\tau) = \int_{-\infty}^{+\infty} \frac{N(\omega)}{|D(\omega)|^2} d\omega$$

whence

$$N(\omega) = \begin{bmatrix} -|\hat{s}_1(\omega)|^2 e^{J\omega(\tau_{12} - \tau_{22})} - |\hat{s}_2(\omega)|^2 e^{J\omega(\tau_{11} - \tau_{21})} + \hat{s}_1(\omega)\hat{s}_2^*(\omega)\, e^{J\omega(\tau_{11} - \tau_{22})} \\ + \hat{s}_1^*(\omega)\hat{s}_2(\omega)\, e^{J\omega(\tau_{12} - \tau_{21})} \end{bmatrix} . e^{J\omega\tau}$$

and

$$|D(\omega)|^2 = 4\sin^2\frac{\omega}{2}(\tau_{11} + \tau_{22} - \tau_{12} - \tau_{21})$$

A sample (but sub-optimal) solution in this case consists in optimizing the numerator $N$ only.

The cross-correlation $\Gamma_{12}$ can then be approximated by:

$$\Gamma_{12}(\tau) \approx \int_{-\infty}^{+\infty} N(\omega)\, d\omega$$

Replacing $N(\omega)$ by its value an expression is obtained which is a function only of the $\gamma_{ij}$ corresponding to the autocorrelations and cross-correlations between the measured signals $s_i$ and $s_j$:

$$\Gamma_{12}(\tau) \cong -\gamma_{11}(\tau+\tau_{12}-\tau_{22}) - \gamma_{22}(\tau+\tau_{11}-\tau_{21}) + \gamma_{12}(\tau+\tau_{11}-\tau_{22}) + \gamma_{21}(\tau+\tau_{12}-\tau_{21})$$

It is recalled that the distance $r_{ij}$ can be approximated by:

$$r_{ij} \approx r_j - \langle \boldsymbol{n}_j, \boldsymbol{c}_i \rangle$$

Thus, replacing $r_{ij}$ in this approximate expression and integrating the phase term

$$e^{-J\omega\frac{r_j}{c}}$$

in $S_j(\omega)$ finally leads to an expression of the estimator of $\Gamma_{12}$ which is as follows:

$$
\begin{aligned}
\Gamma_{12}(\tau) \approx & - \gamma_{11}\left(\tau - \frac{<\boldsymbol{n}_2,\boldsymbol{c}_1>}{c} + \frac{<\boldsymbol{n}_2,\boldsymbol{c}_2>}{c}\right) \\
& - \gamma_{22}\left(\tau - \frac{<\boldsymbol{n}_1,\boldsymbol{c}_1>}{c} + \frac{<\boldsymbol{n}_1,\boldsymbol{c}_2>}{c}\right) \\
& + \gamma_{12}\left(\tau - \frac{<\boldsymbol{n}_1,\boldsymbol{c}_1>}{c} + \frac{<\boldsymbol{n}_2,\boldsymbol{c}_2>}{c}\right) \\
& + \gamma_{21}\left(\tau - \frac{<\boldsymbol{n}_2,\boldsymbol{c}_1>}{c} + \frac{<\boldsymbol{n}_1,\boldsymbol{c}_2>}{c}\right)
\end{aligned}
$$

where $\boldsymbol{n}_j$ = the unit vector of $(OX_i)$ with $i = 1, 2$. However:

$$
\begin{aligned}
<\boldsymbol{n}_1,\boldsymbol{c}_1> &= -\frac{D}{2}\cos\theta_1 \\
<\boldsymbol{n}_1,\boldsymbol{c}_2> &= \frac{D}{2}\cos\theta_1 \\
<\boldsymbol{n}_2,\boldsymbol{c}_1> &= -\frac{D}{2}\cos\theta_2 \\
<\boldsymbol{n}_2,\boldsymbol{c}_2> &= \frac{D}{2}\cos\theta_2
\end{aligned}
$$

Where the distance between sensors is written is D. Then:

$$
\begin{aligned}
\Gamma_{12}(\tau) \approx & -\gamma_{11}\left(\tau + \frac{D}{c}\cos\theta_2\right) \\
& -\gamma_{22}\left(\tau + \frac{D}{c}\cos\theta_1\right) \\
& +\gamma_{12}\left(\tau + \frac{D}{2c}(\cos\theta_1 + \cos\theta_2)\right) \\
& +\gamma_{21}\left(\tau + \frac{D}{2c}(\cos\theta_1 + \cos\theta_2)\right)
\end{aligned}
$$

The functional to be minimized relative to $(\theta_1, \theta_2)$ is thus:

$$R_{12} = \int_{-\infty}^{+\infty} \Gamma_{12}^2(\tau)\, d\tau$$

Sign ambiguity between $\theta_1$ and $\theta_2$ is removed by analyzing the half-plane containing the sources and assumed to be known <u>a priori</u>.

The invention is not limited to the examples described and shown, since various modifications can be made thereto without going beyond this ambit.

Without further elaboration, it is believed that one skilled in the art can, using the preceding description, utilize the present invention to its fullest extent. The preceding preferred specific embodiments are, therefore, to be construed as merely illustrative, and not limitative of the remainder of the disclosure in any way whatsoever. Also, any preceding examples can be repeated with similar success by substituting the generically or specifically described reactants and/or operating conditions of this invention for those used in such examples.

Throughout the specification and claims, all temperatures are set forth uncorrected in degrees Celsius and, all parts and percentages are by weight, unless otherwise indicated.

The entire disclosure of all applications, patents and publications, cited herein are incorporated by reference herein.

From the foregoing description, one skilled in the art can easily ascertain the essential characteristics of this invention and, without departing from the spirit and scope thereof, can make various changes and modifications of the invention to adapt it to various usages and conditions.